Exploring the Tera-Scale at the LHC: Status and Perspectives

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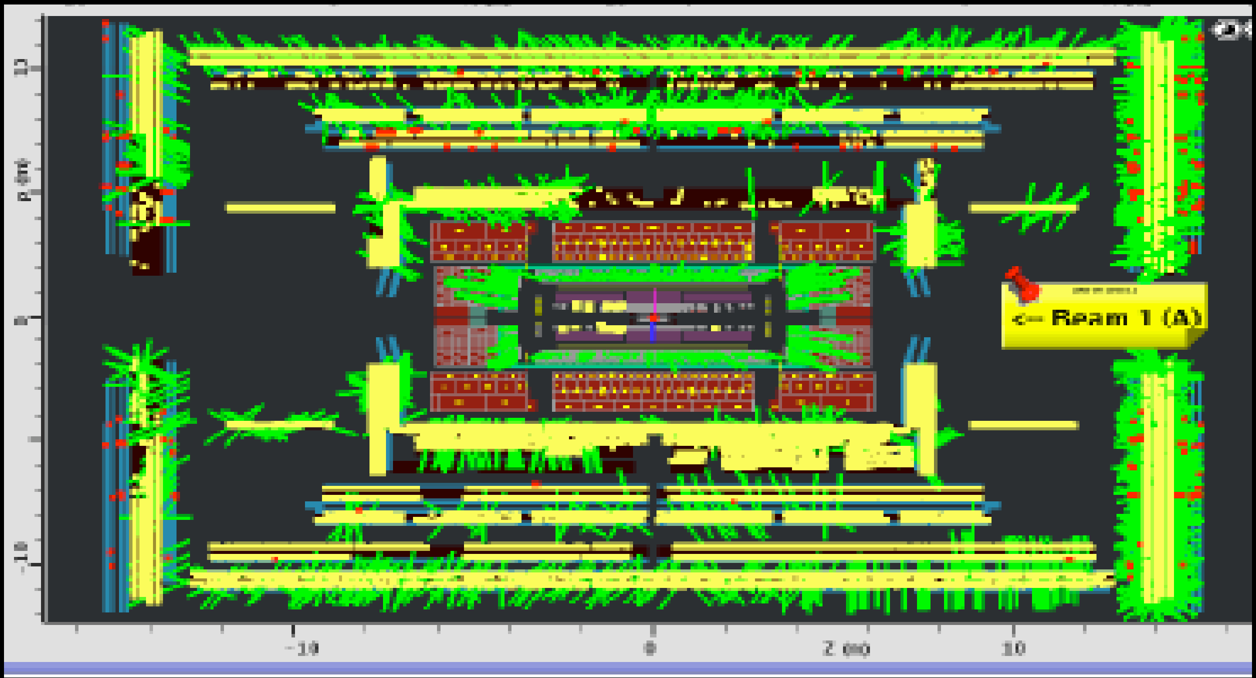


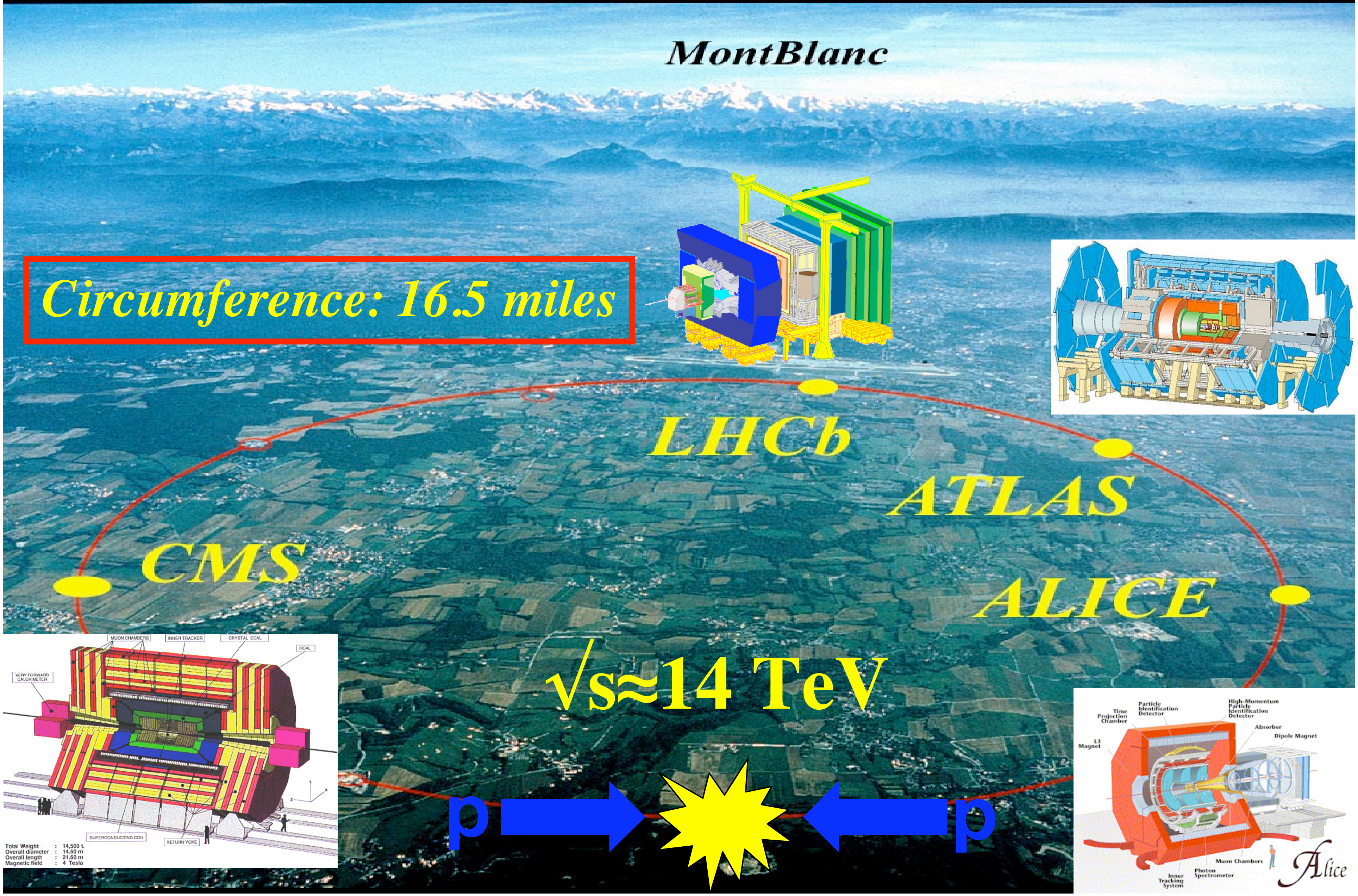
UC Berkeley, December 8th, 2008

Outline

- The Large Hadron Collider
- The Physics Questions
- The Experimental Challenge
- The status of the LHC
- Conclusions

The Large Hadron Collider

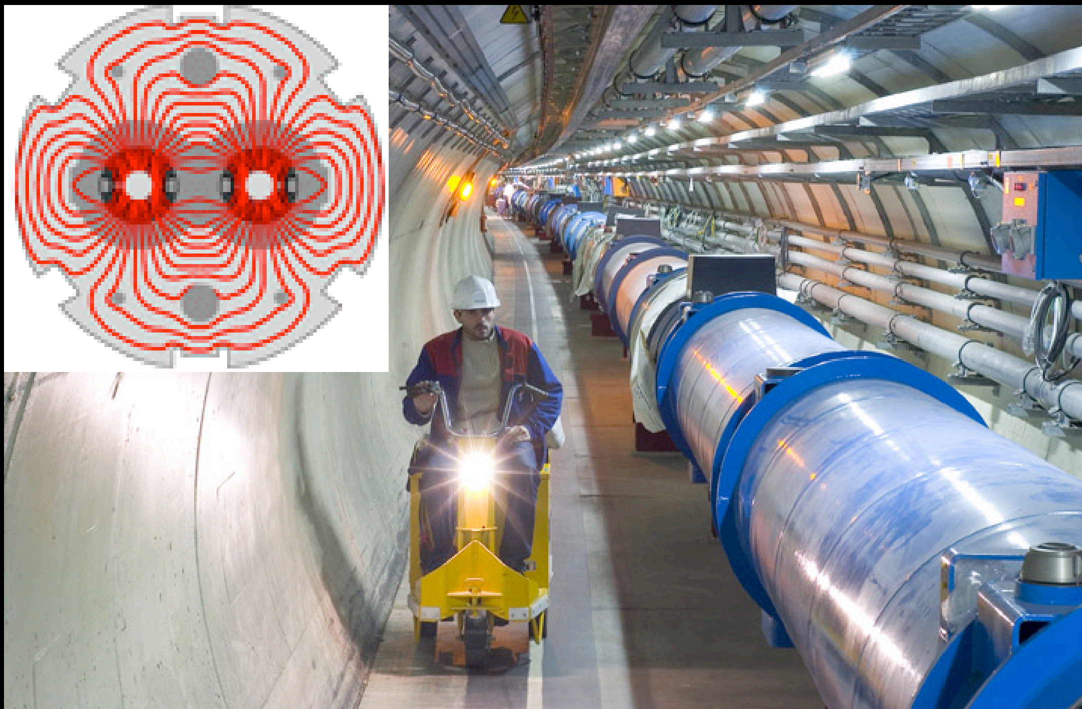
The Large Hadron Collider (LHC)



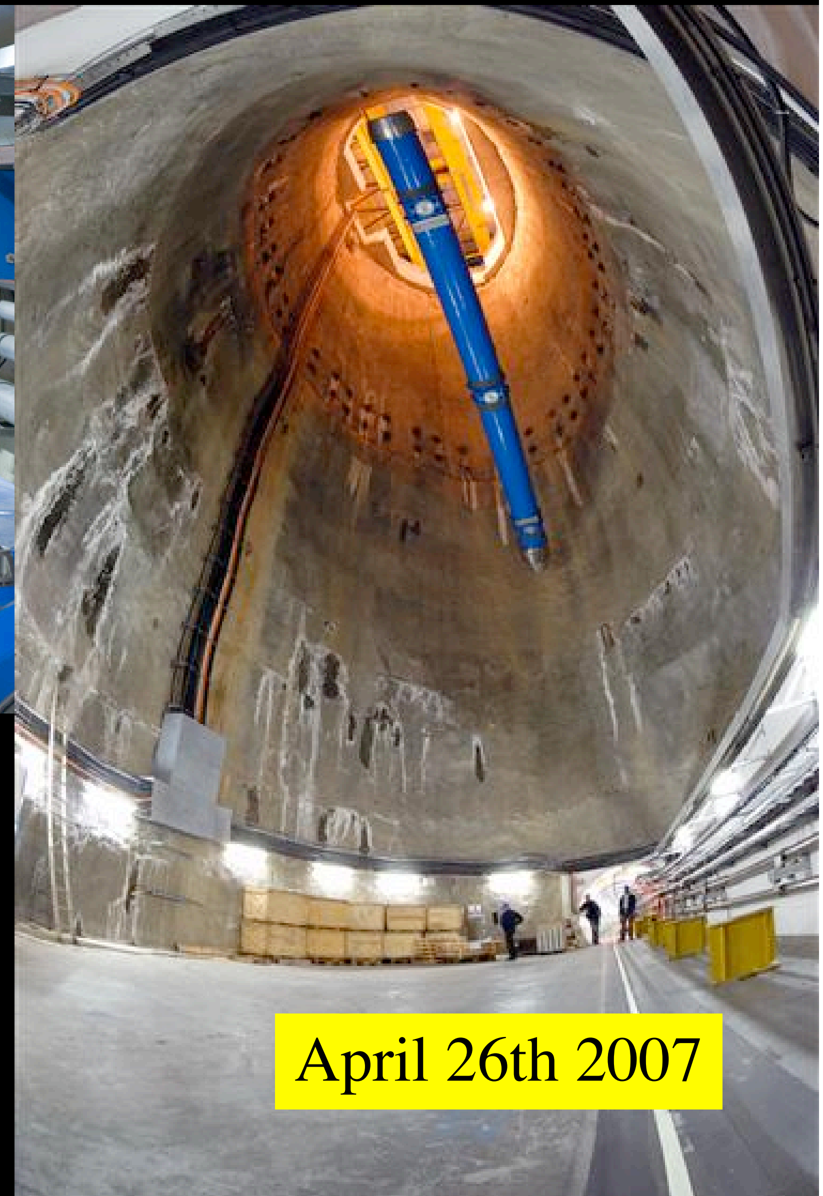
LHC in the Bay

– protons make a full turn 11254 times per second

LHC Accelerator



- 30,000 tons of 8.4T dipole magnets (1232 magnets)
- Cooled to 1.9K with 96 tons of liquid helium
- Energy of beam = 362 MJ
  - 15 kg of Swiss chocolate



Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^{\,2}}{A}$$

revolving frequency: f_{rev}=11254/s
#bunches: n_{bunch}=2835
#protons / bunch: N_p= 10^{11}
Area of beams: A~40 μm

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Cross section σ:
Given by Nature
(calc. by theorists)

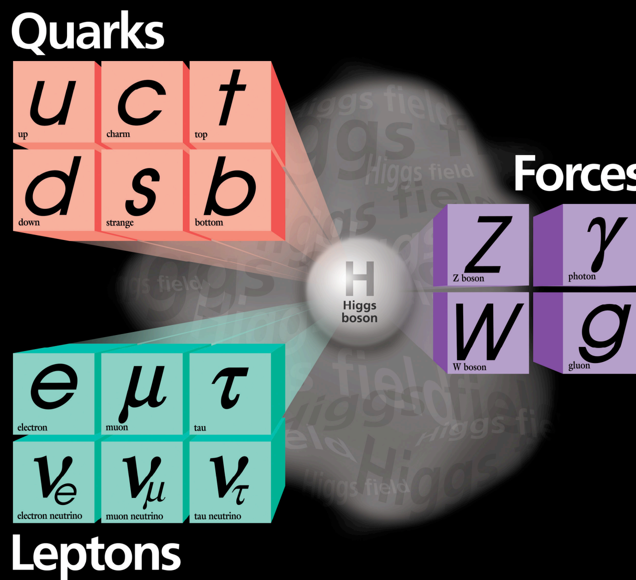
Efficiency:
optimized by
experimentalist

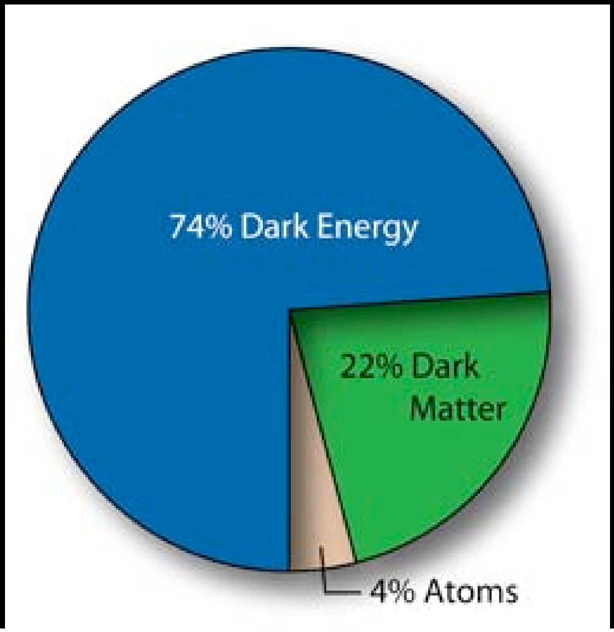
Ability to observe something depends on N_{obs}

Physics Questions

What Do We Hope to find at LHC?

- Answers to very fundamental and simple questions:
  - **Why do particles have mass?**
    - Possible answer: The Higgs boson
  - **Why is gravity so weak?**
    - Possible answers: supersymmetric particles, extra spatial dimensions
  - **What is the Dark Matter?**
    - Possible answer: the lightest supersymmetric particle
  - **The unexpected …**



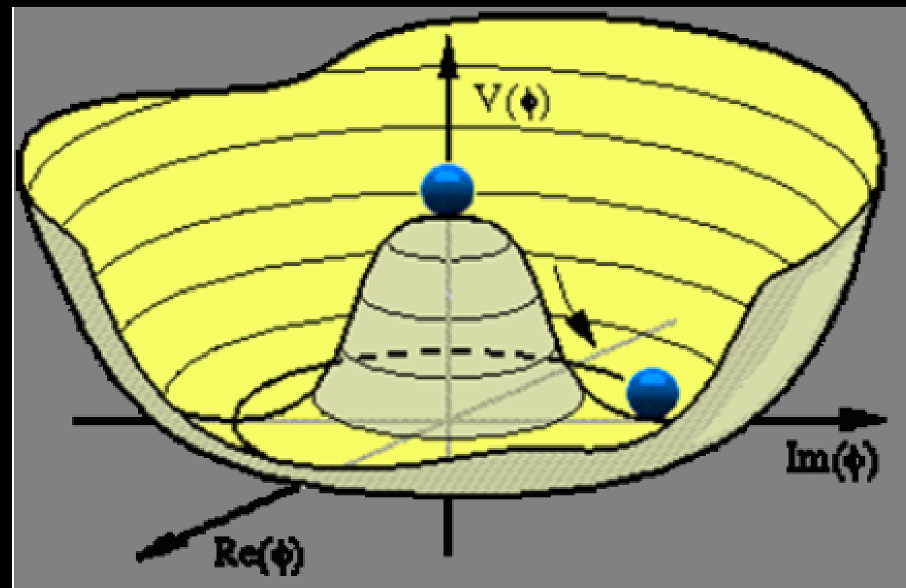


The Higgs Mechanism

- 1964
  - P. Higgs
  - R. Brout, F. Englert
- New scalar self-interacting field with 4 d.o.f.:

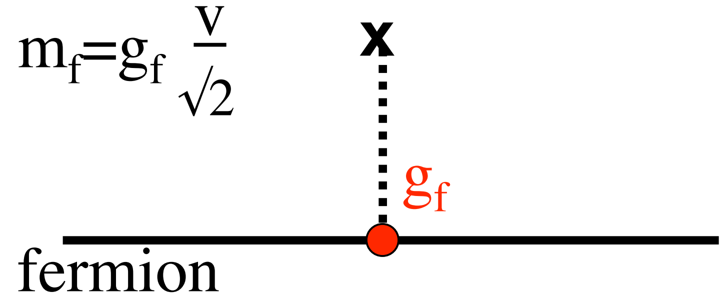
$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$

- Ground state: non-zero-value breaks electroweak symmetry generating
  - 3 Goldstone bosons: $W^\pm_L, Z_L$
  - 1 neutral Higgs boson
- Masses of fermions m_f proportional to unknown Yukawa couplings g_f

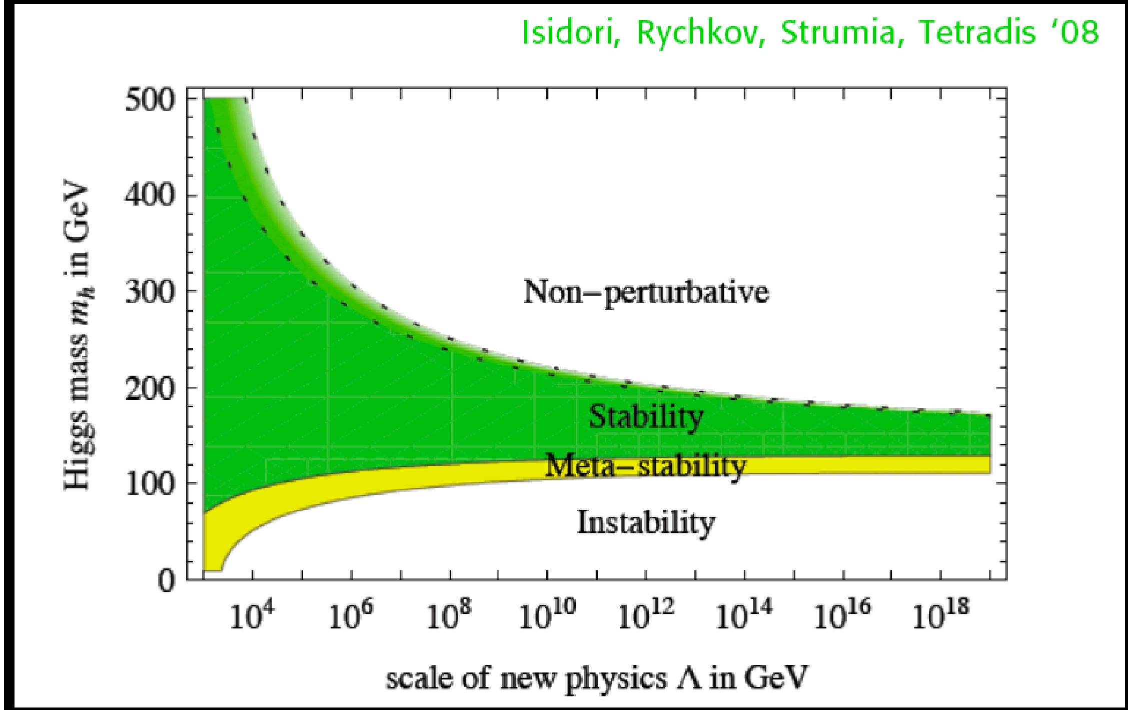


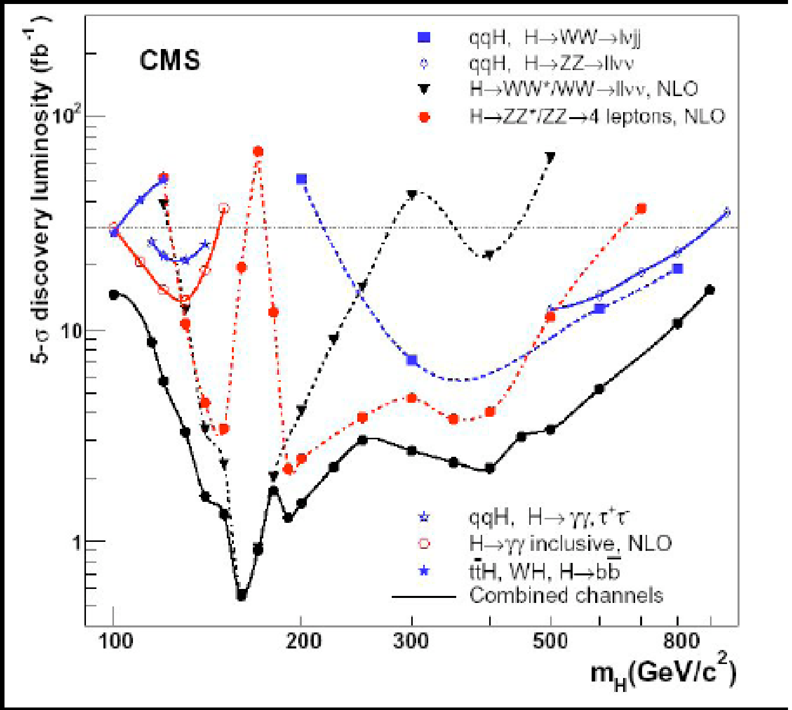
$\langle\Phi^0\rangle = v/\sqrt{2}$, where $v = 246$ GeV.

$$m_f = g_f \frac{v}{\sqrt{2}}$$



Will the Higgs Boson be found?

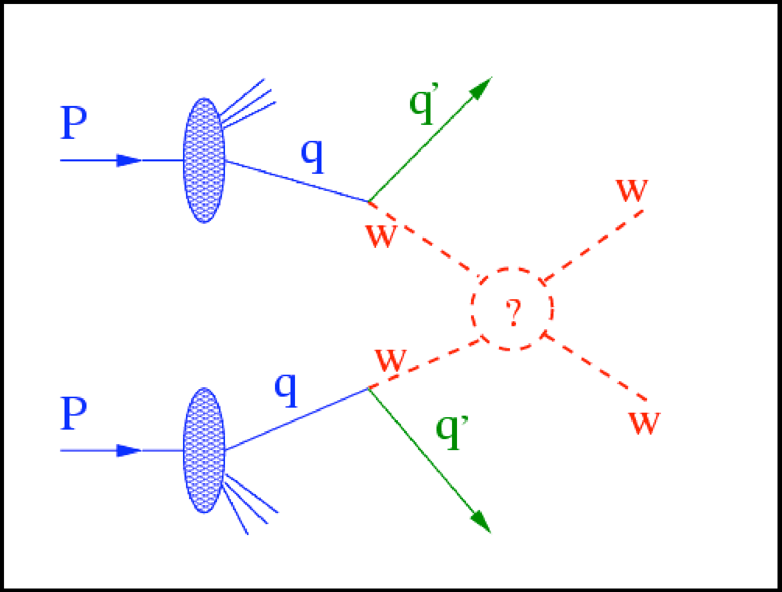




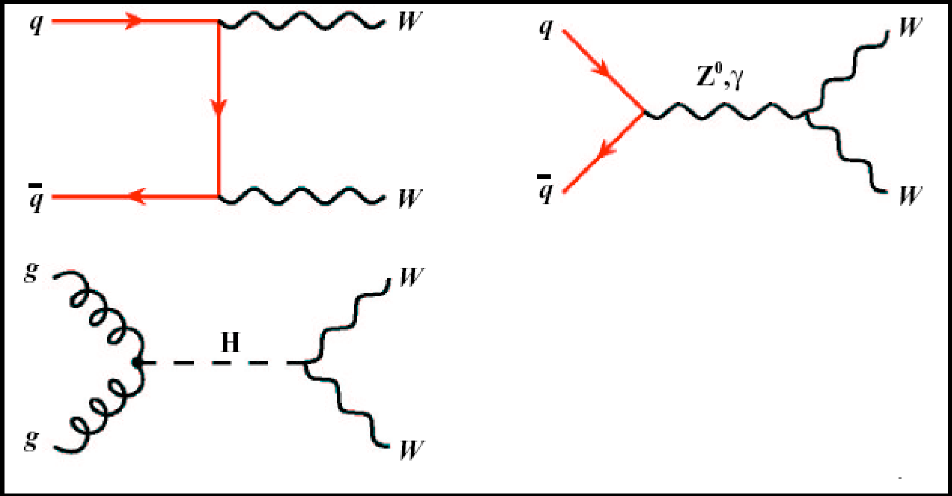
- Theoretically bound to be less than 160-500 GeV
- Experimentally bound to be >114 GeV
- Findable at LHC over full mass range with ~20 fb^{-1}

The Higgs boson will be found at LHC if it exists

What if there is no Higgs Boson?



Standard Model processes

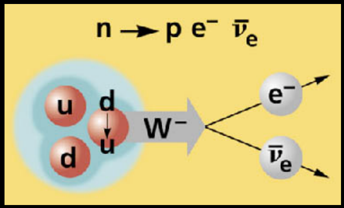


- $W_L W_L$ cross section increases with energy
  - perturbative expansion in s: $\sigma \propto s^2/v^2 + s^4/v^4 \ldots$
    - Violates unitarity at $\sqrt{s}$~1.2 TeV!
  – Thus some new physics must be there
    - E.g. W bosons are composite (similar to pion-pion scattering in 1960's)

Will also be probed by LHC

The "finetuning problem"

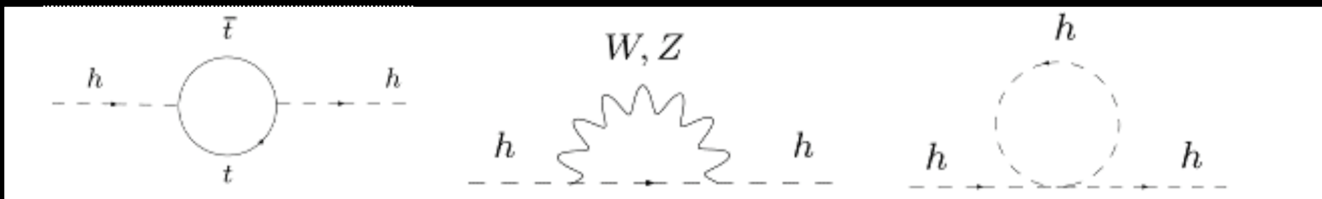
- Why is gravity is so much weaker than the weak force?
  - Newton: G_N=6.67 x 10^{-11} m^3kg/s^2 ~10^{-38} GeV^{-2}
  - Fermi: G_F=1.17 x 10^{-5} GeV^{-2}



- Or why is the W boson mass so small?
  - Weak scale: M_W ~$1/M_{weak}=1/\sqrt{G_F}$ ~10^2 GeV
  - Natural scale: $M_{Planck}=1/\sqrt{G_N}$~10^{19} GeV

⇒**"Finetuning" required to make W and Higgs mass small**

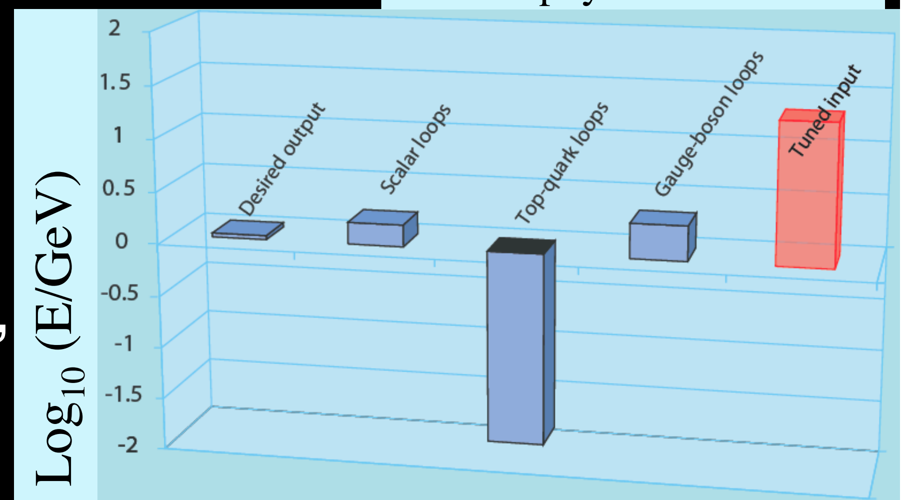
Finetuning Problem

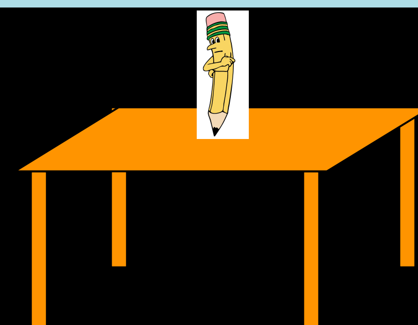


$$m^2_H \approx (200\ \mathrm{GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$$

- Free parameter $m_H{}^{tree}$ "finetuned" to cancel huge corrections
- Considered to be "unnatural"
  - Some unknown ad-hoc parameter introduced with superb precision

$M_{new\ physics}$=5 TeV



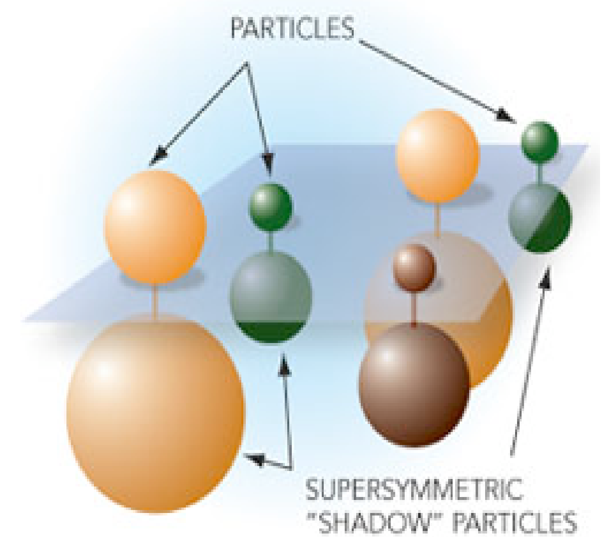


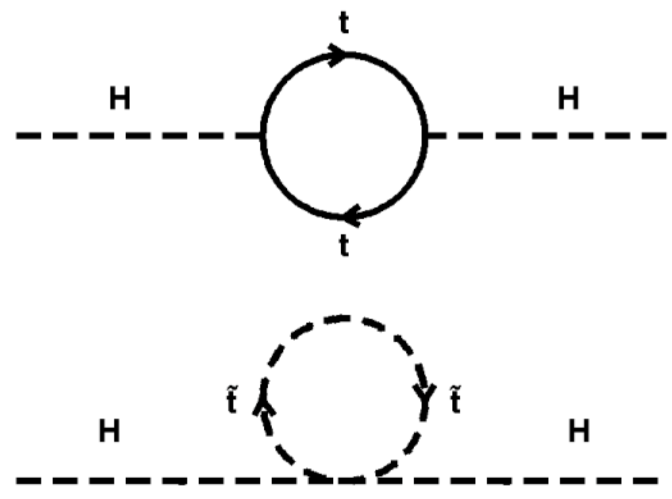
Theoretically not satisfactory

Solving the finetuning problem

- "Supersymmetric" particles
  - Each standard model particle has a partner, e.g.:
    - Electron => Selectron
    - Quark => Squark
    - Photon => Photino
    - W boson => Wino
  - New loops can cancel the old loops
    - Size of loops naturally the same if particle masses similar
  - No tuned ad-hoc parameter needed

Superpartners!





Already happened in History!

- May seem "crazy" to have another set of particles introduced to solve aesthetic problem
- Analogy in electromagnetism:
  - Free electron has Coulomb field: $\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$
  - Mass receives corrections due to Coulomb field:
    - $(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\text{Coulomb}}.$
    - With $r_e<10^{-17}$ cm: $0.000511 = (-3.141082 + 3.141593)\ \text{GeV}.$
  - Solution: the positron!

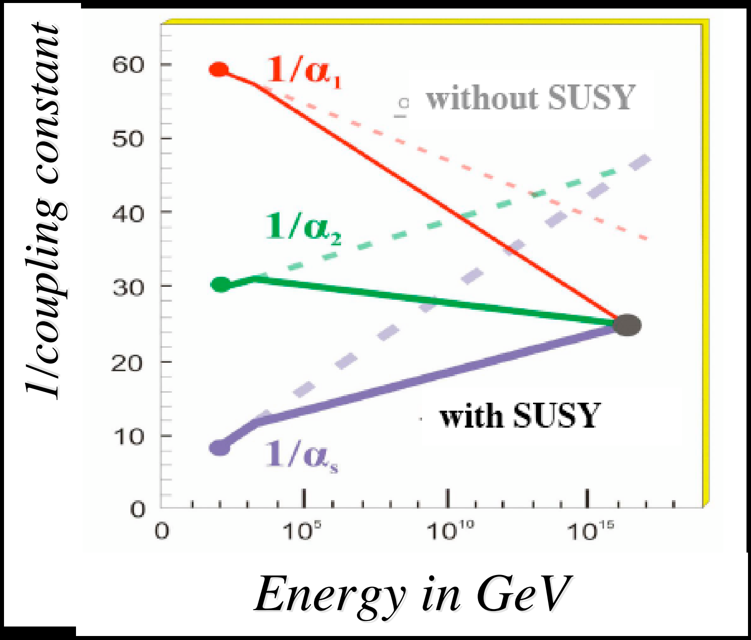
$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}\ .$$

$<<m_ec^2$

Hitoshi Murayama

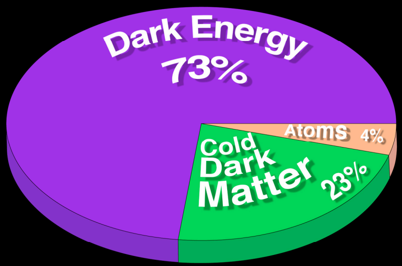
Problem was not as bad as today's but it resulted in new particle species: anti-particles

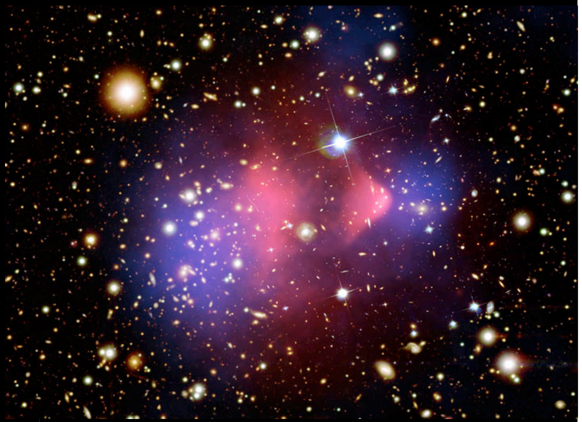
More virtues of Supersymmetry (SUSY)



- Electromagnetic, strong and weak force unify!
  - Miss unification in SM (barely)
  - Unify in SUSY if masses about 1 TeV!

- Includes candidate for dark matter with mass ~ 0.1-1 TeV
  - Cosmology data point to such particles
  - 5 times more than ordinary matter

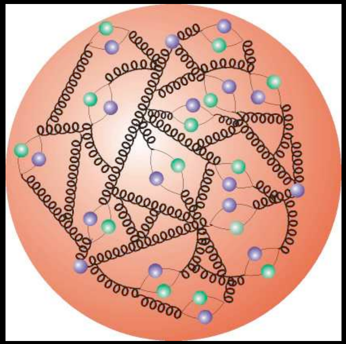




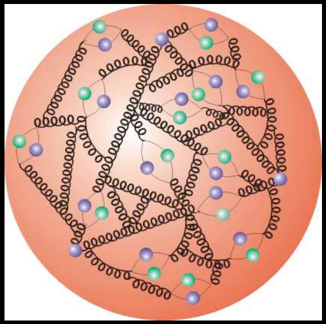
If SUSY particles are the solution to finetuning problem they will be found at the LHC

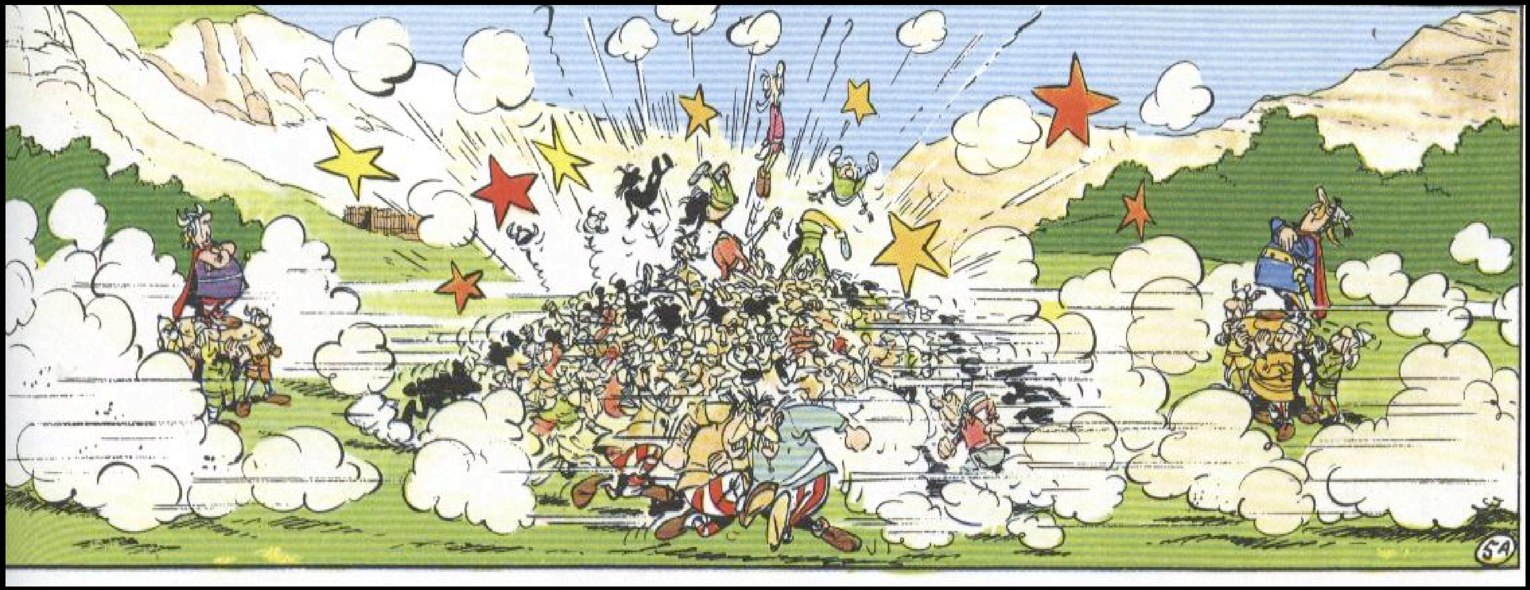
The Experimental Challenge

Proton-proton collisions



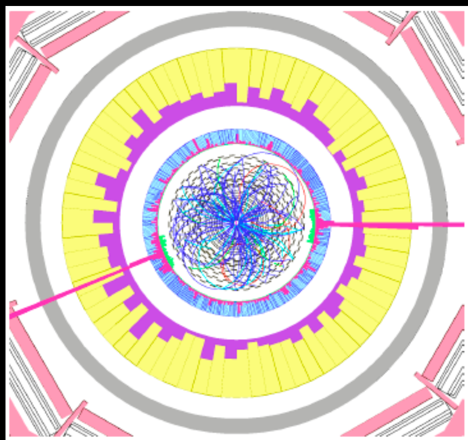
7 TeV → ← 7 TeV



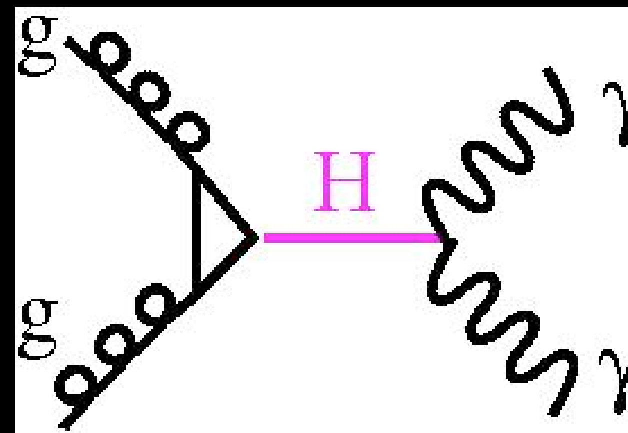


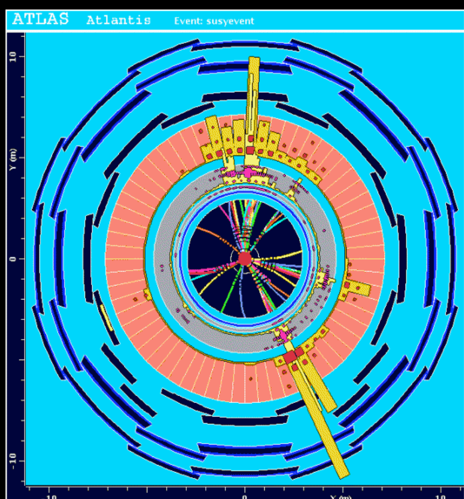
Complex events need to be resolved by high resolution detectors

Experimental Observation vs Theory

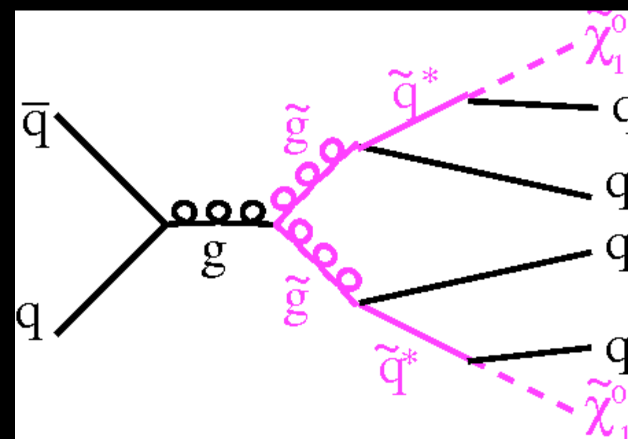


Higgs





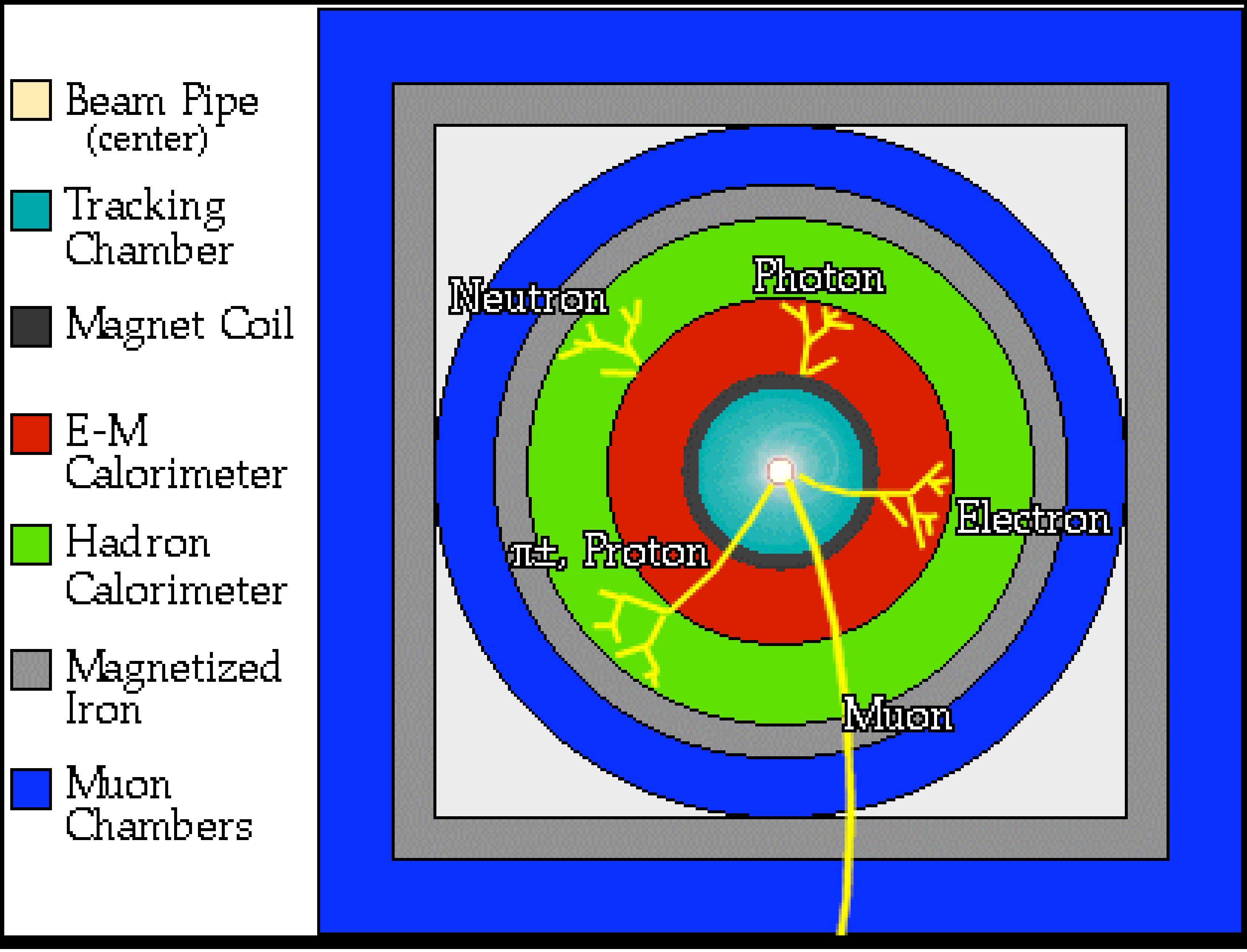
Supersymmetry



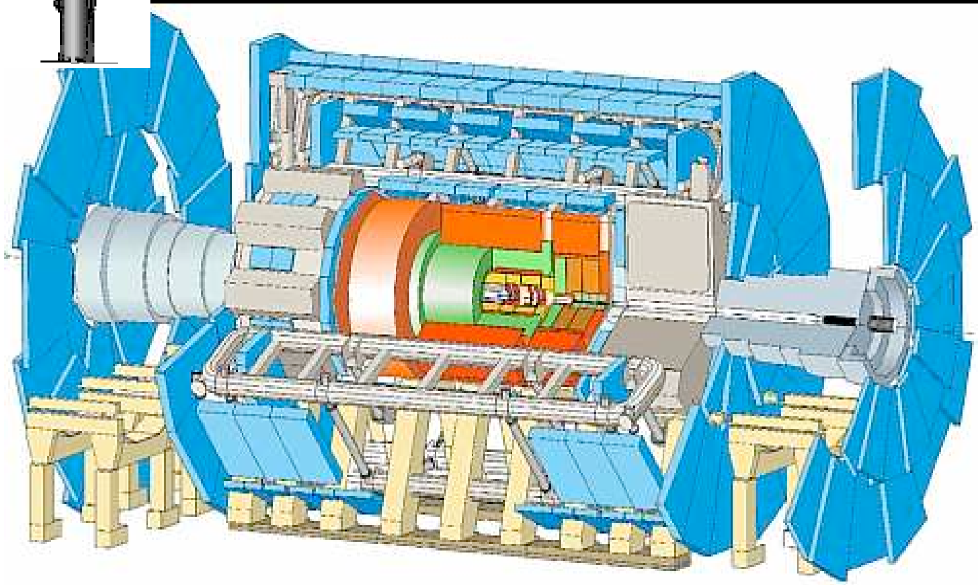
- Measured hits in detector
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

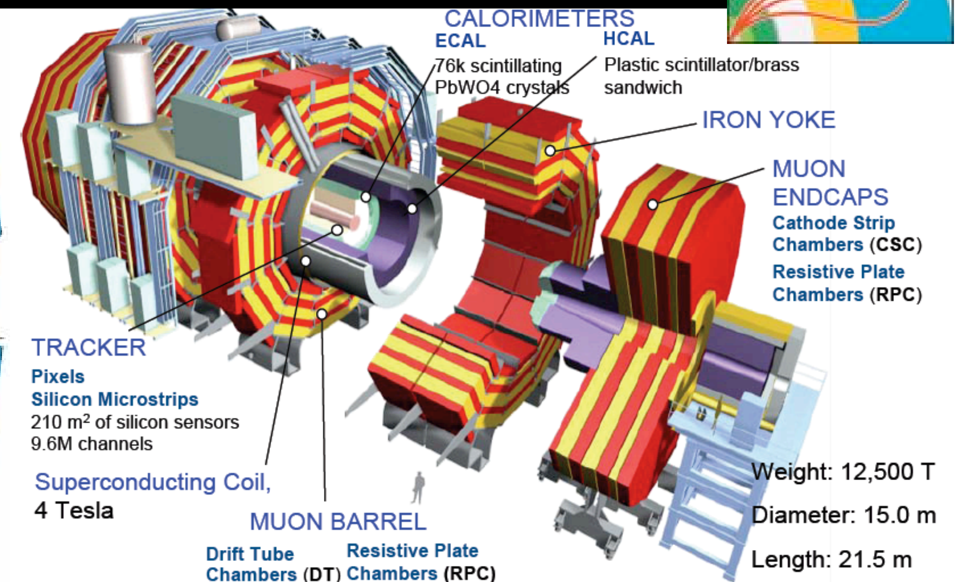
Particle Identification

- Detector designed to separate electrons, photons, muons, neutral and charged hadrons



ATLAS and CMS Detectors





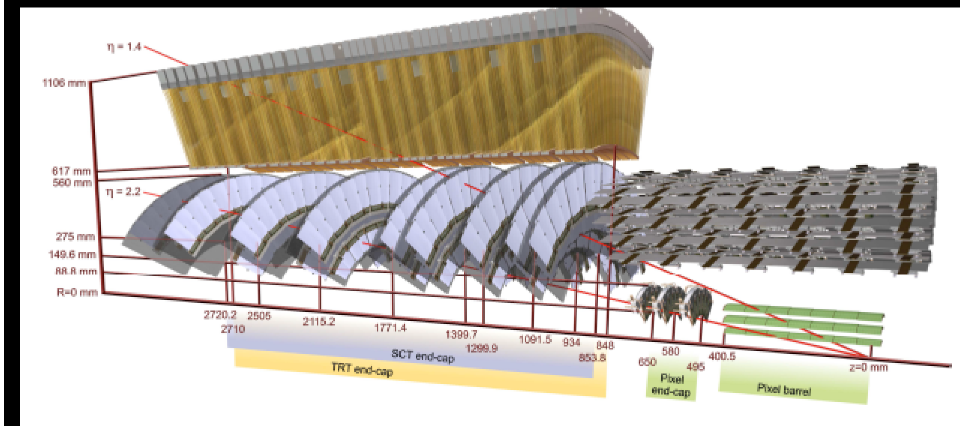
	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

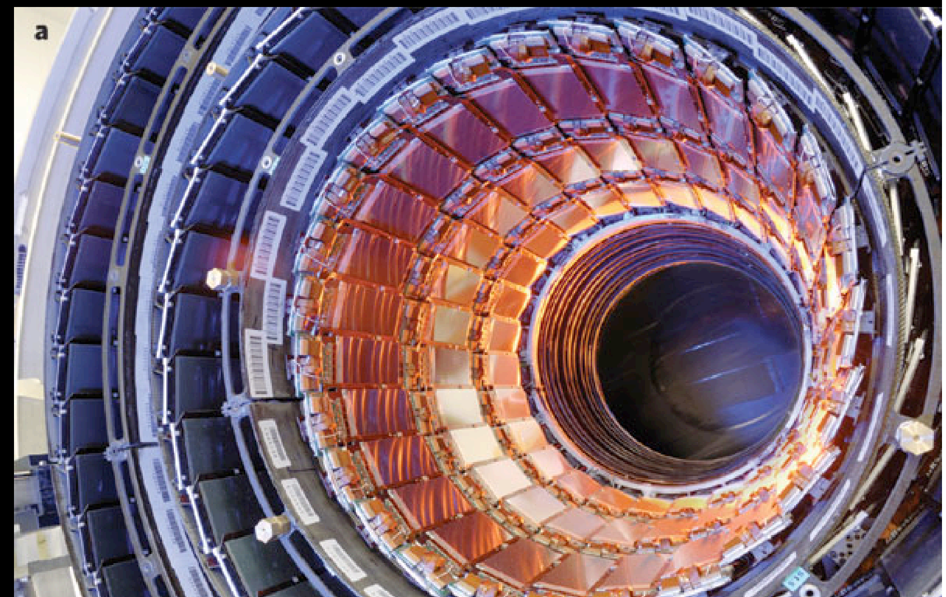
ATLAS and CMS in Berlin

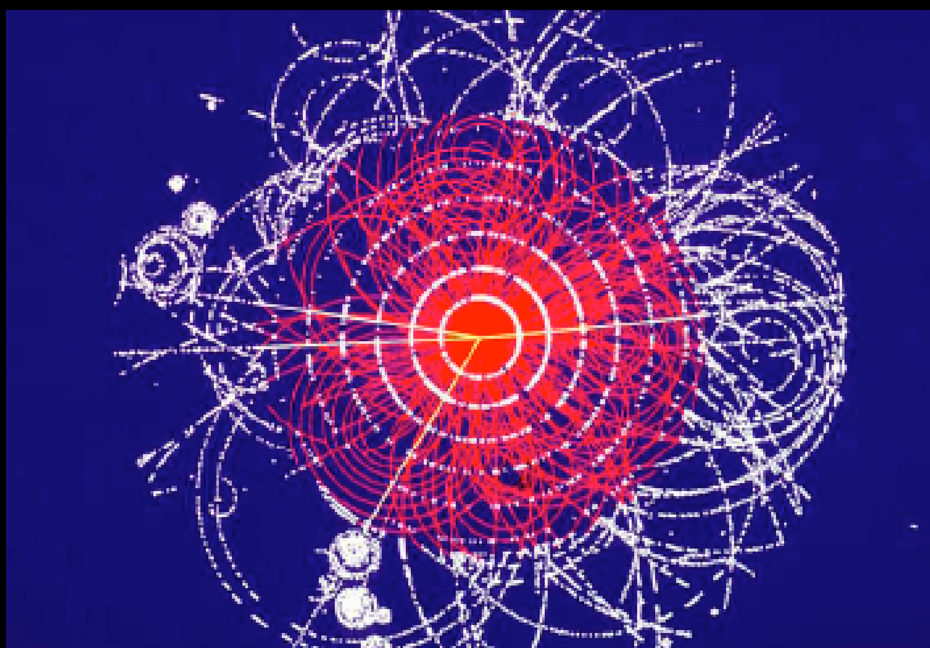
Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower

Tracking Detectors

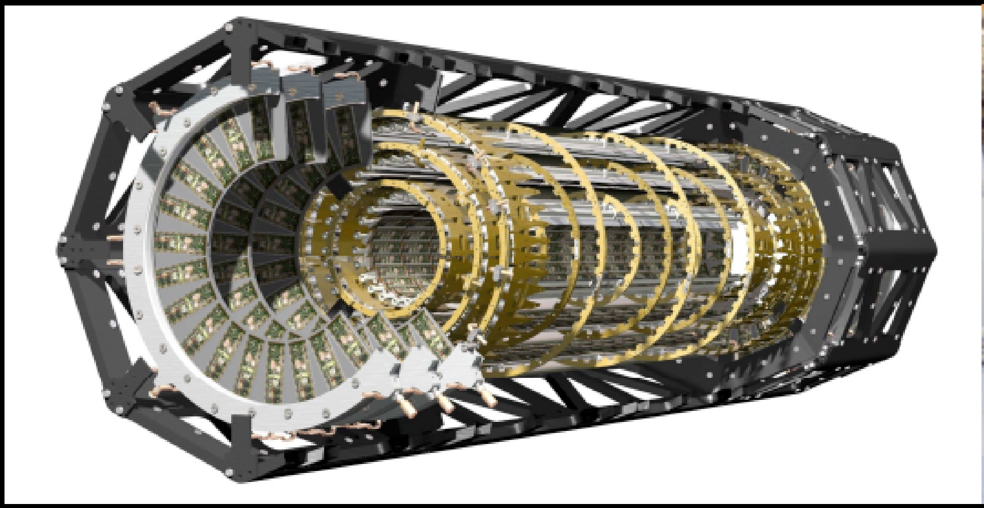


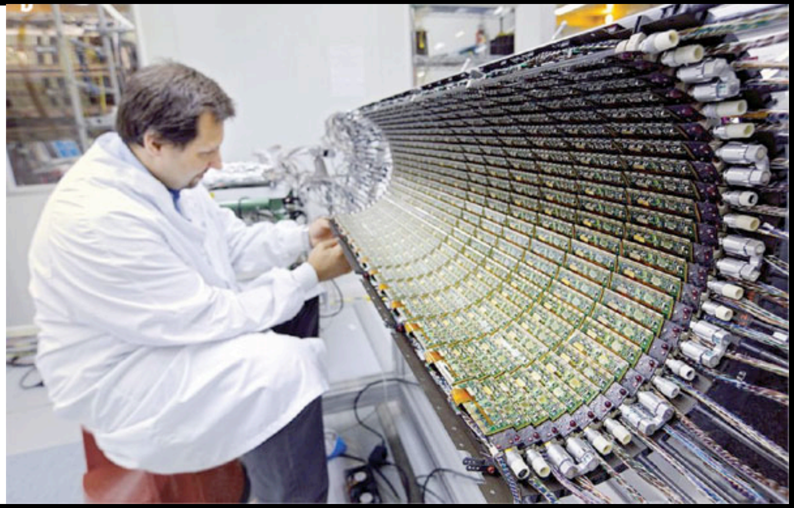




- **Tracking detectors**
  - ATLAS: TRT, silicon strips + pixels
  - CMS: silicon strips + pixels
- **CMS silicon area: 200 m²**
  - Size of a football field

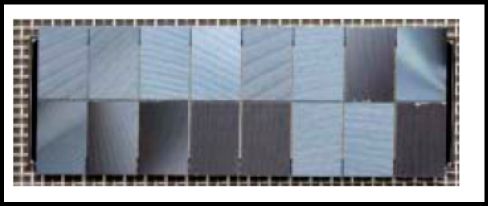
The ATLAS Pixel Detector



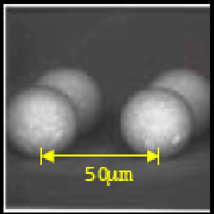


module

2 cm

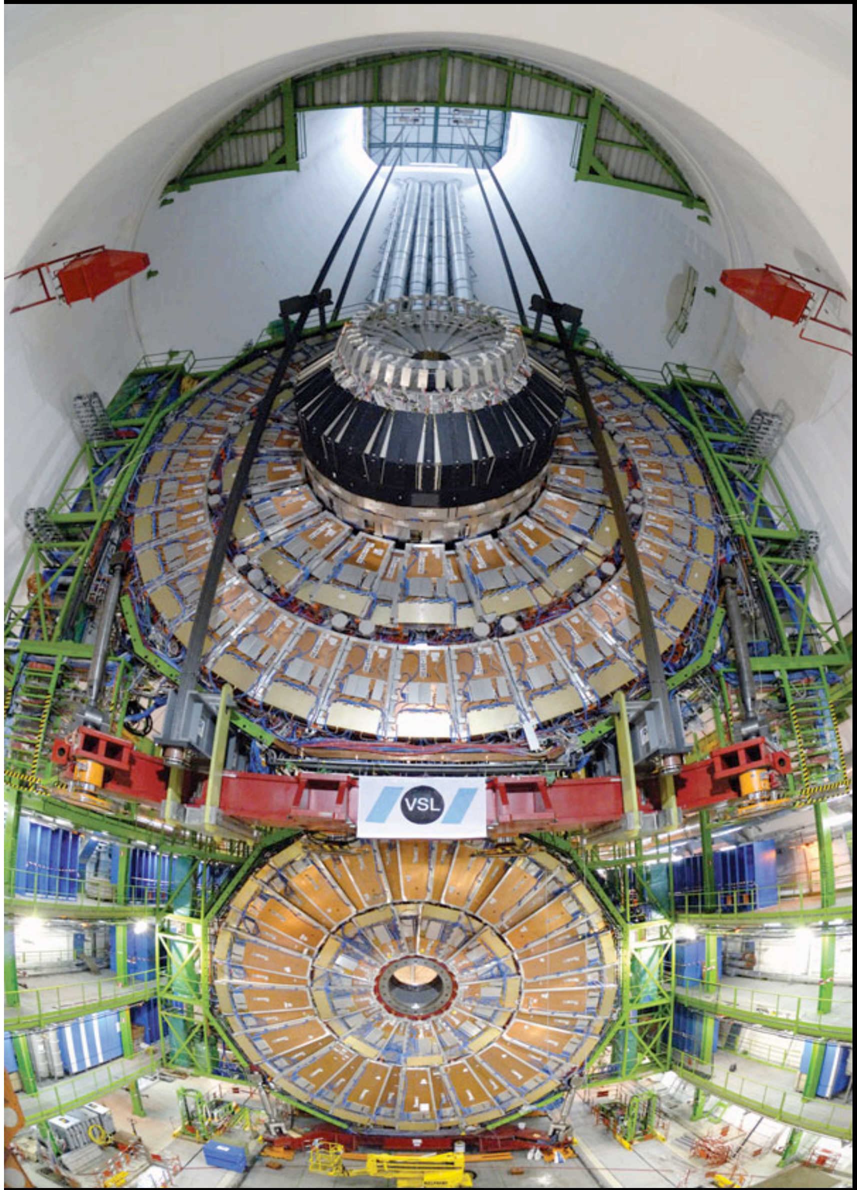


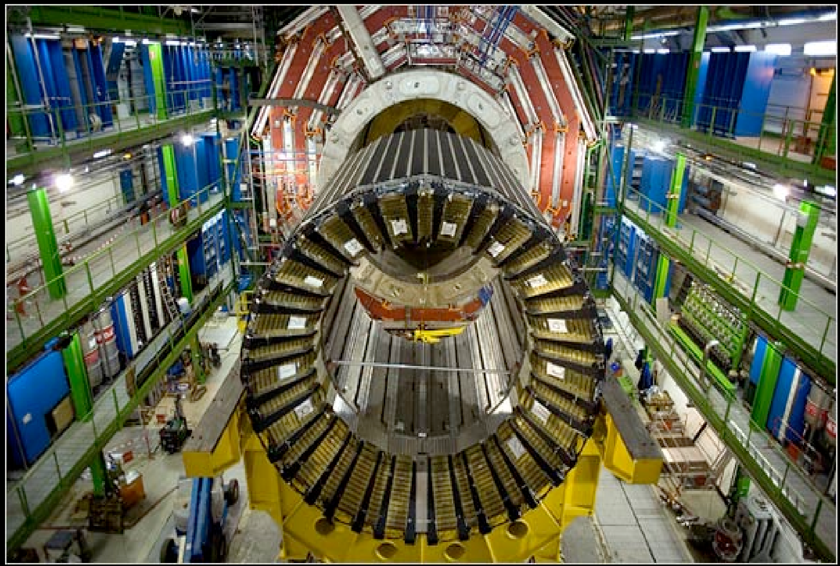
6 cm

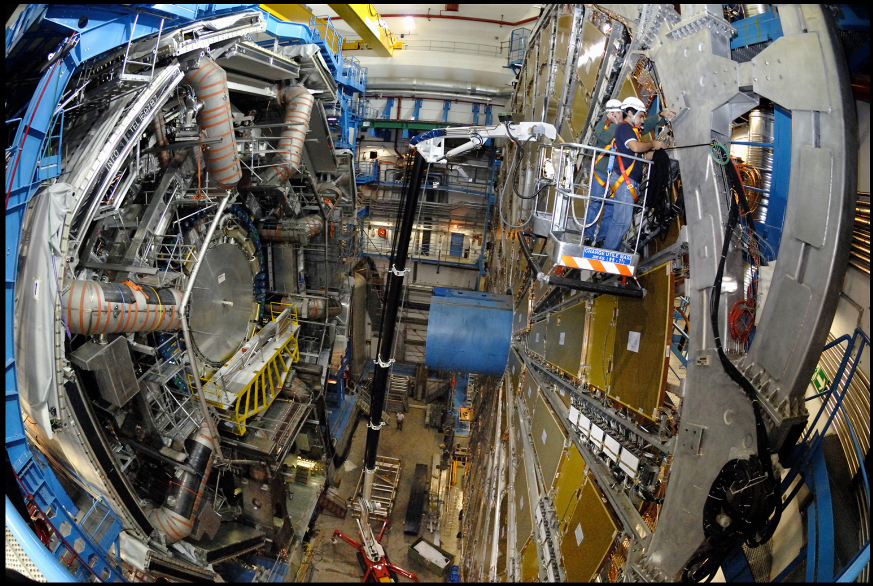


- Cylinder: L=1.4 m , R=12.25 cm
- 80 million individual pixels arranged in modules:
  - 16 chips per module, 2880 pixels per chip => 46080 pixels/module
  - Distance between pixels: 50 μm ("pitch")
- Designed and built largely in Berkeley

Muon Systems and Calorimeters





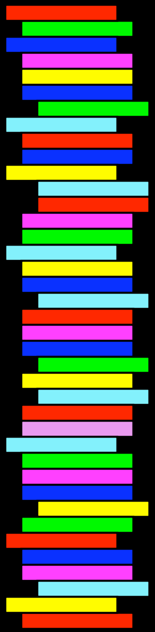


2000 Physicists from all over the World

(including 400 PhD students)
+ many technician and engineers

Enormous Data Volumes

- **Pushing the computing limits!**
  - 1 second of LHC data: 1000 GigaBytes
    - **10,000 sets of the Encyclopedia Britannica**
  - 1 year of of LHC data: 10,000,000 GB
    - **25 km tower of CD's (~2 x earth diameter)**
  - 10 years of LHC data:
    - **All the words spoken by humankind since its appearance on earth**

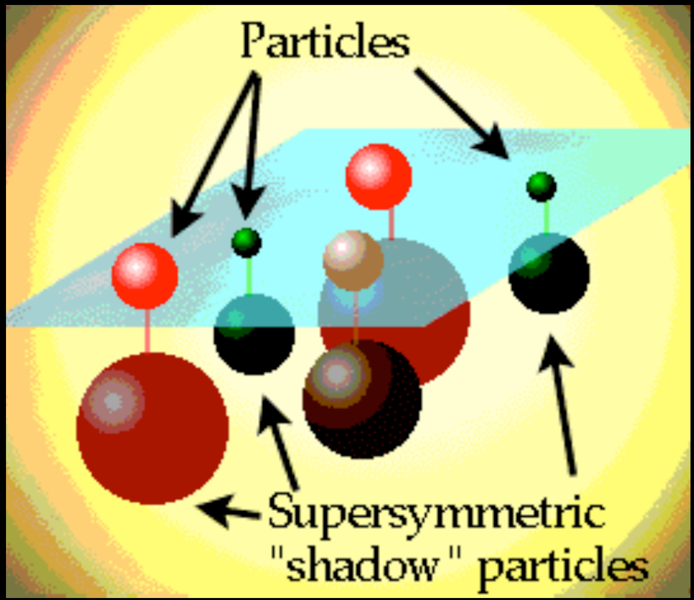


- **Solution: the "Grid"**
  - Global distribution of CPU power
    - More than 100 CPU farms worldwide share computing power

Some Example Analyses

Finding the Higgs boson:
-with photons
-with Z-bosons

Finding a Supersymmetric World



Rates of Physics Processes

- Much increased rates compared to previous collider

Process (mass)	Tevatron $\sqrt{s}$ =2 TeV	LHC $\sqrt{s}$=14TeV	Ratio
$W^{\pm}$ (80 GeV)	2600	20000	~10
tt (2x172 GeV)	7	900	~100
gg->H (120 GeV)	1	40	~40
$\tilde{\chi}^{+}_{1}\tilde{\chi}^{0}_{2}$ (2x150 GeV)	0.1	1	~10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	~1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	~20000
Z' (1 TeV)	0.1	30	~300

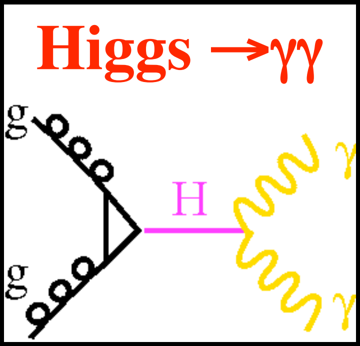
- **Excellent discovery opportunity for heavy particles**
  - Biggest jump in energy since SppS that discovered W's and Z's

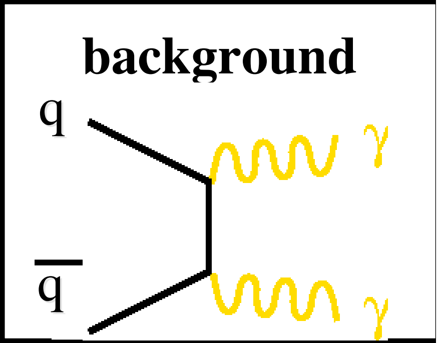
Finding the Higgs Boson (with photons)

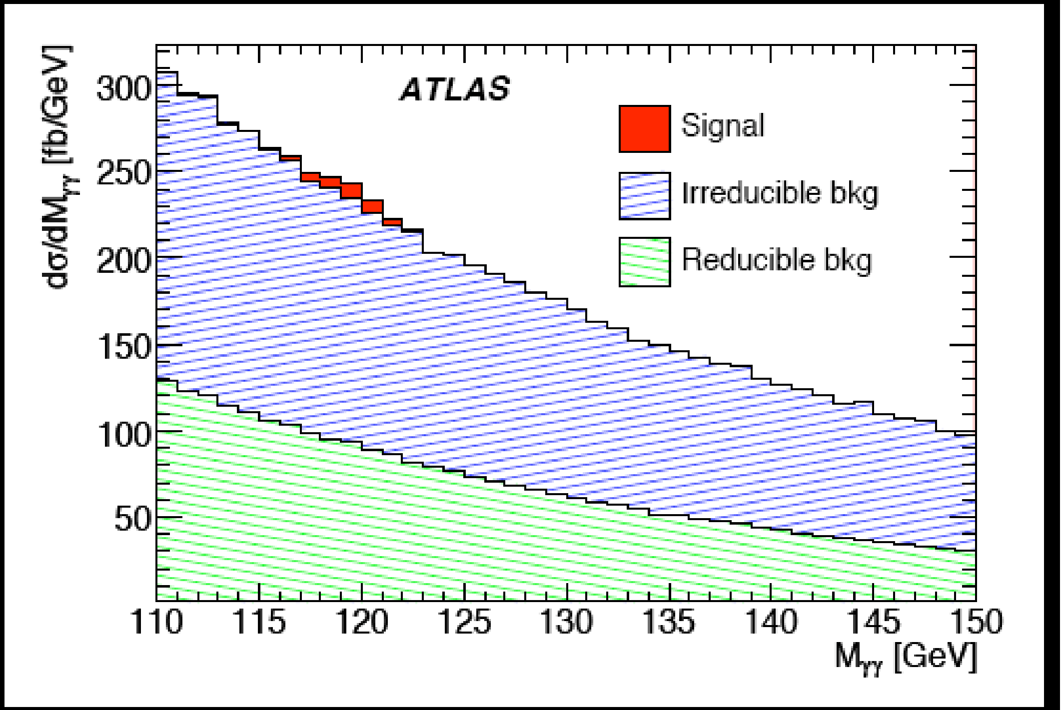
- Find 2 high energy photons
  - If m_H<130 GeV/c^2
- Separate signal from backgrounds
  - Backgrounds can look exactly the same
  - but for γ's from Higgs:

$$M(H)=M(\gamma\gamma)=\sqrt{[(E_1+E_2)^2-(p_1+p_2)^2]}$$

- Difficult analysis
  - Requires ~10-30 fb^{-1}



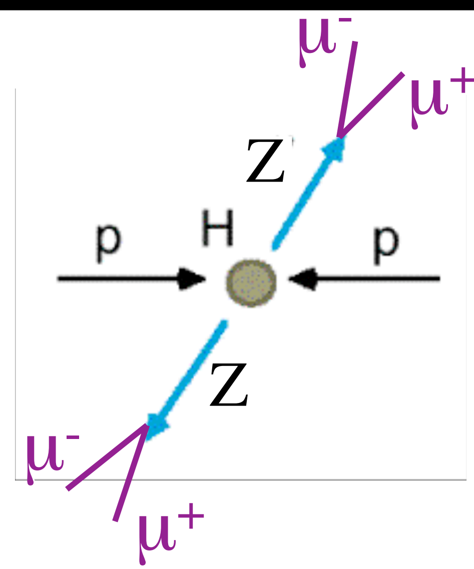




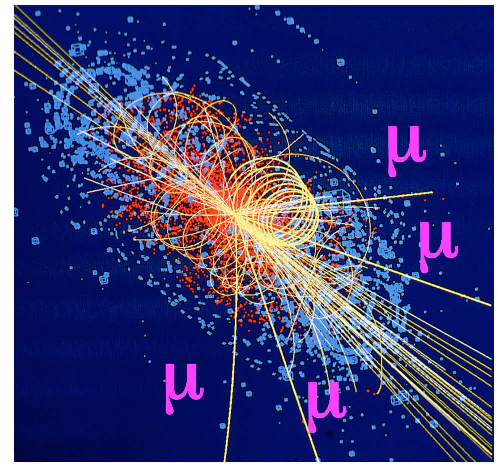
Discovery possible in 2012-2013 (?)

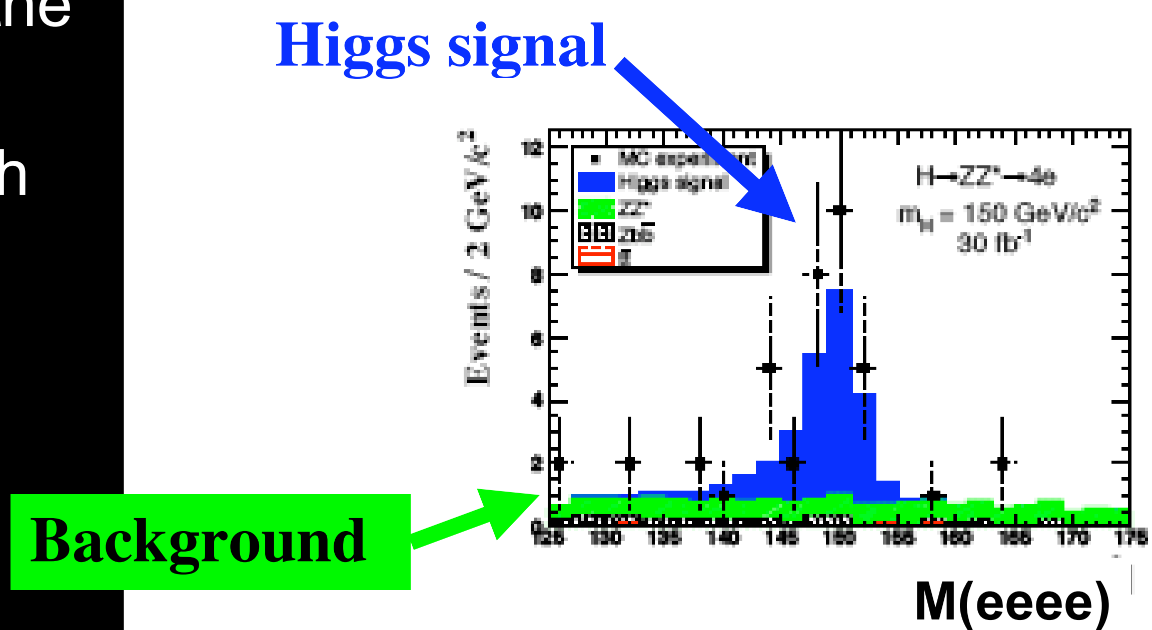
Finding the Higgs Boson (with Z's)

- Find 4 high energy muons or electrons
  - If $M(H)>130$ GeV/c^2
- Separate signal from backgrounds
  - Again calculating the invariant mass
  - Backgrounds much smaller than in diphoton case:
    - Easier!

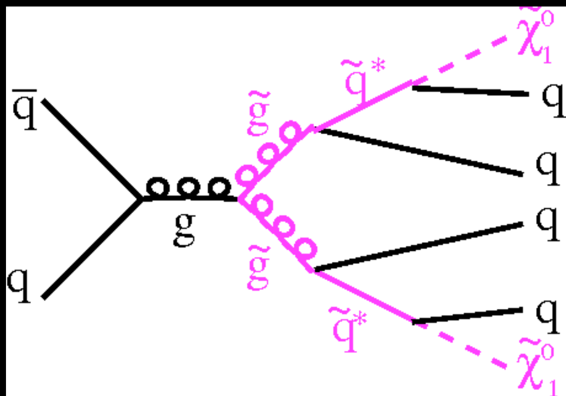


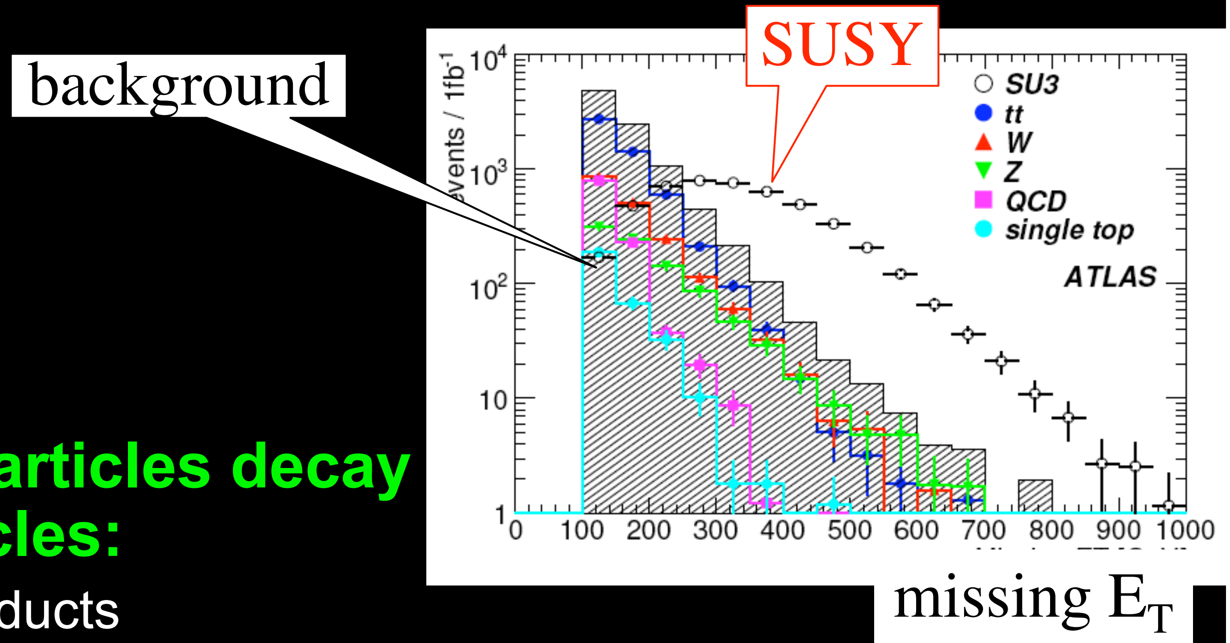
simulated event





Finding a Supersymmetric World





- **Supersymmetric particles decay into ordinary particles:**
  - Measure decay products
  - Dark matter particle ($\tilde{\chi}_1^0$) escapes detector unseen:
    - Momentum balance tell us presence of dark matter particles ("missing E_T")
- **Search strategy:**
  - Search for many high energy particles plus large missing E_T

Discovery possible in ≥2010

Many Other Possibilities…

Current Status of the LHC

Original LHC Startup Plan

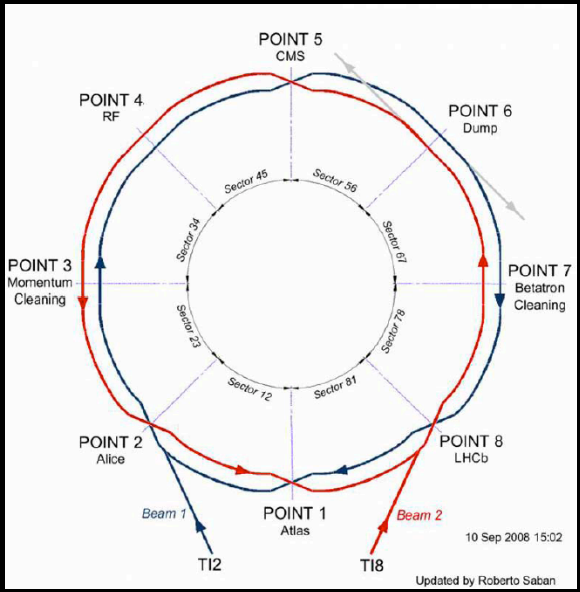
- September 10th 2008:
  - First circulating beam at 450 GeV
- 2-4 weeks later
  - Collisions of beams at 450 GeV
- November-December ‘08
  - Collide beams at 5 TeV (expected L~10-100 pb^{-1})
    - 7 of the 8 sectors had been commissioned up to 5.5 TeV
- December ‘08 - June ‘09
  - Shutdown to commission machine to design energy
- June ‘09-November ‘09
  - A few fb^{-1} of luminosity at $\sqrt{s}$=14 TeV (1 fb^{-1} ~2M Z-bosons)
- Then… continue to improve each year
  - 3 years with 10 fb^{-1} per year
  - Then 3 years with 100 fb^{-1} per year

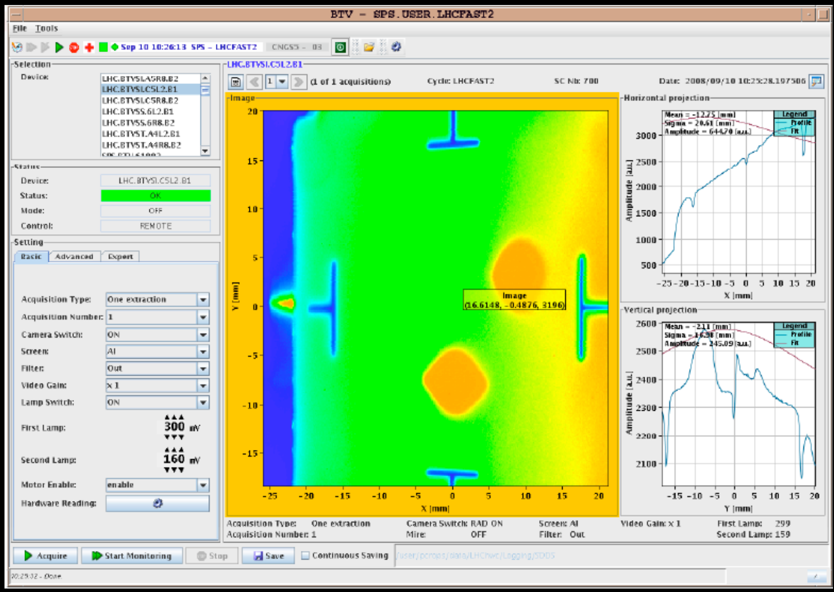
September 10th 2008

- First beam circulation broadcasted live on TV worldwide
- Worked very well: accomplished within <1h

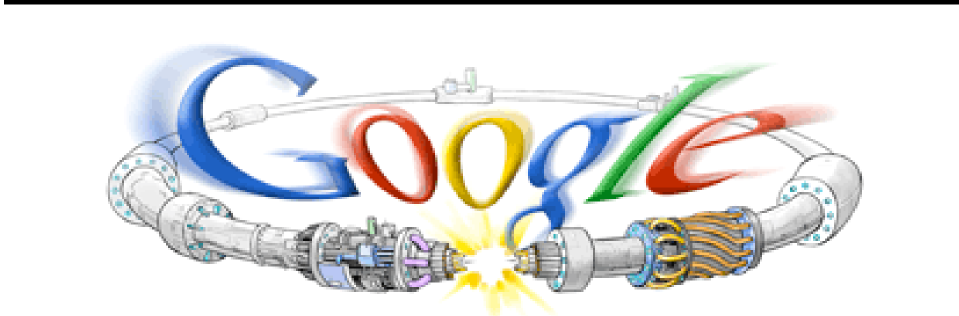
Beam circulation

- The accelarator physicists were amazed how well it all worked
  - Lot's of optimism spread in the community
  - The machine looked "great"





In the News…



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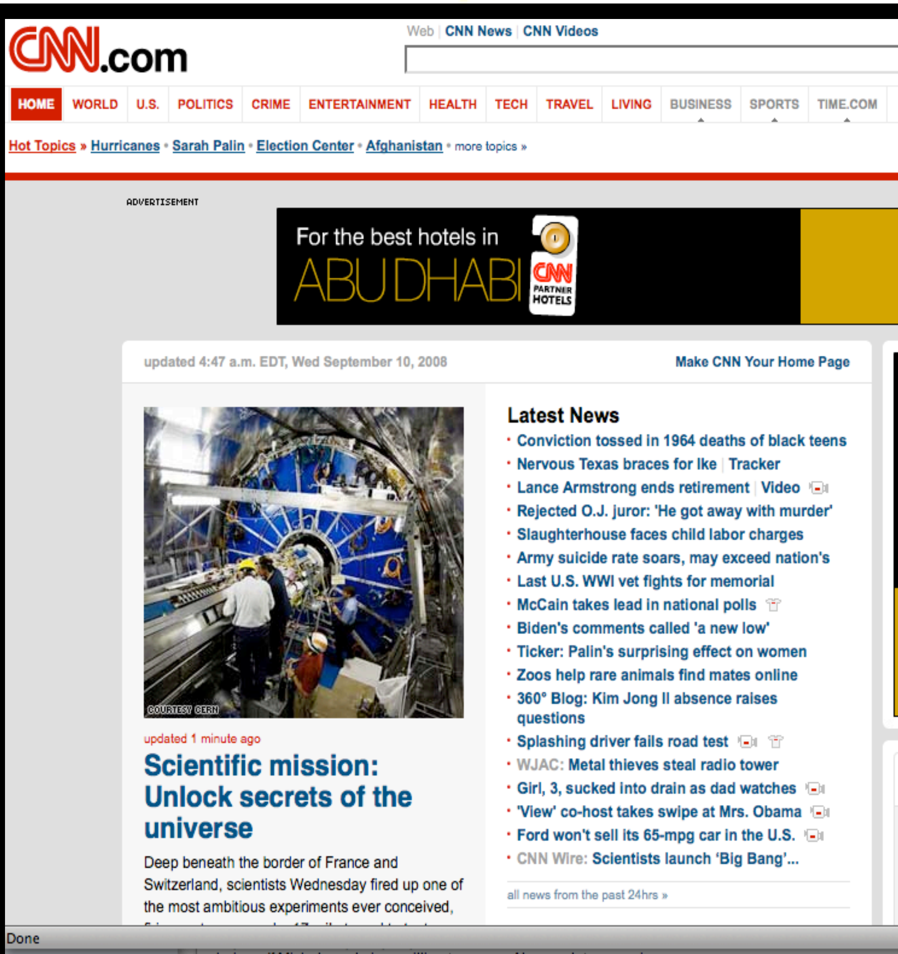
Top stories updated 4:36 a.m. ET Sept. 10, 2008
THE BIG BANG MACHINE
Maximilien Brice / CERN
'Big Bang Machine' comes to life
UPDATED After 14 years of preparation, scientific wonder of the world opens for business with the official startup of Europe's Large Hadron Collider. Story | Interactive: How it works



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Start für Teilchenbeschleuniger
Dem Urknall auf der Spur
In Genf ist der Teilchenbeschleuniger "Large Hadron Collider" (LHC) in Betrieb gegangen. Wissenschaftler wollen mit der weltgrößten Anlage im Atomforschungszentrum CERN den Urknall simulieren und die Materie erforschen. Kritiker des Experiments warnen vor Schwarzen Löchern. [mehr]
Quarks&Co: Das Mikroskop der Physiker [wdr]
Quarks&Co: Interaktiver Teilchenbeschleuniger [wdr]
CERN - das europäische Forschungszentrum
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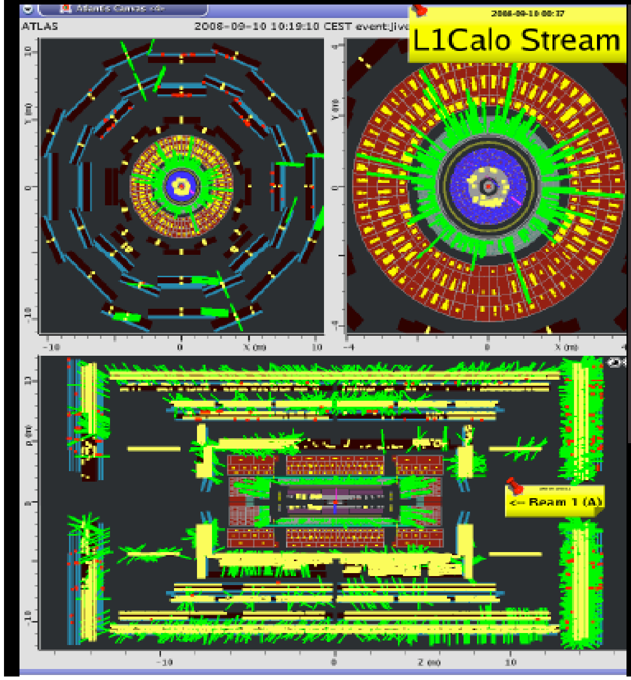
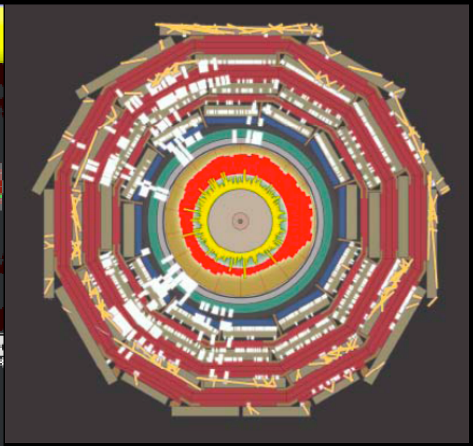
Bilder

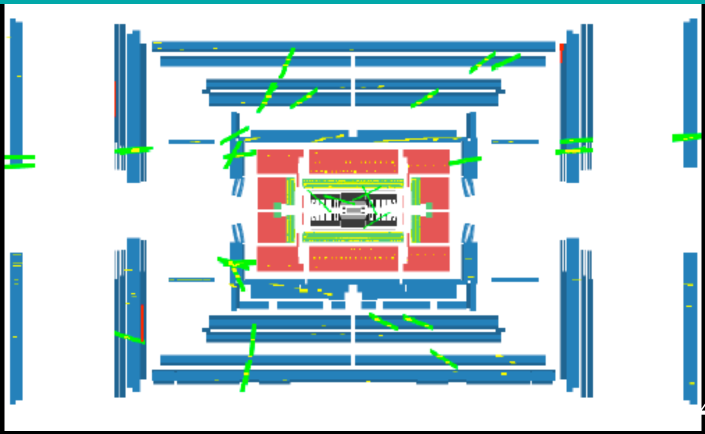
Excitement in ATLAS and CMS

“Splash events”: from beam dump into collimators





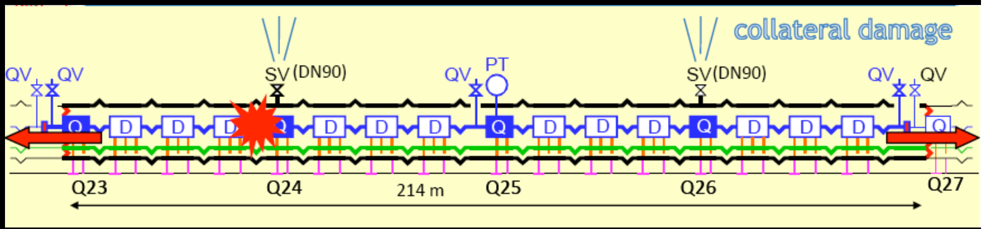
Beam halo muons From circulating beam



September 19th: the problem

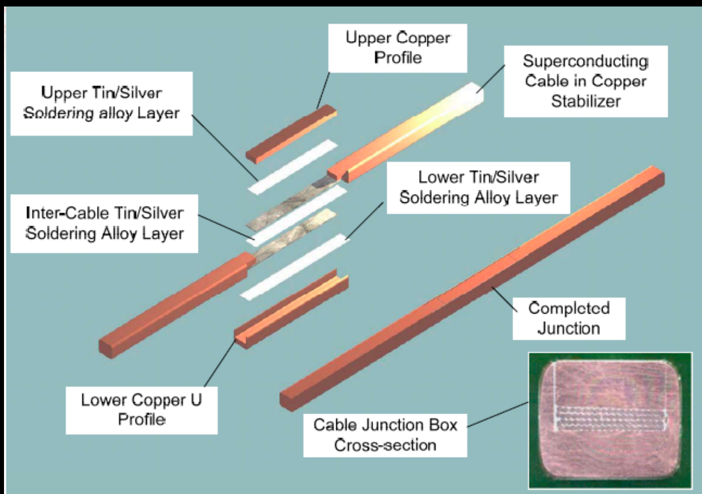
- A (minor) problem occurred with a transformer when trying to bring beams to collisions
  - Meanwhile the remaining 8th sector (sector 34) was commissioned up to 5.5 TeV
  - Ramped to current of 9.3 kA (previously worked up to 7kA)

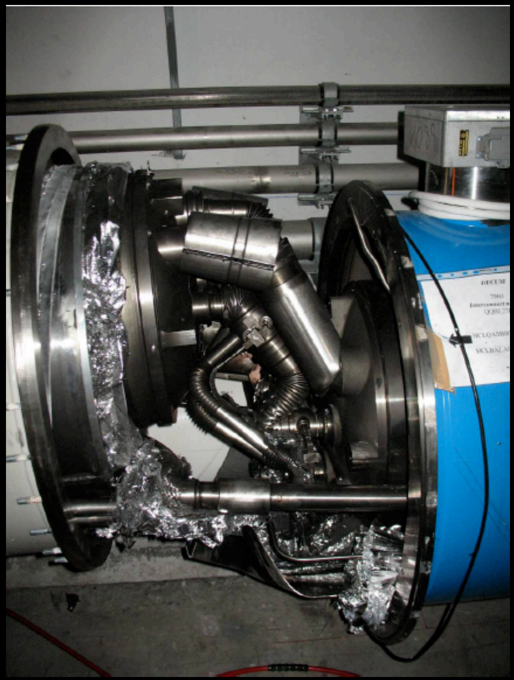
- Major incidence occurred in sector 34 due to faulty connection between a dipole and a quadrupole magnet:
  - Resistive zone developed



  - An arc developed burning a hole into the cryostat
    - 60% of the 600MJ of energy was released
      - Some of the magnets moved by 0.5m
    - About 100 magnets quenched

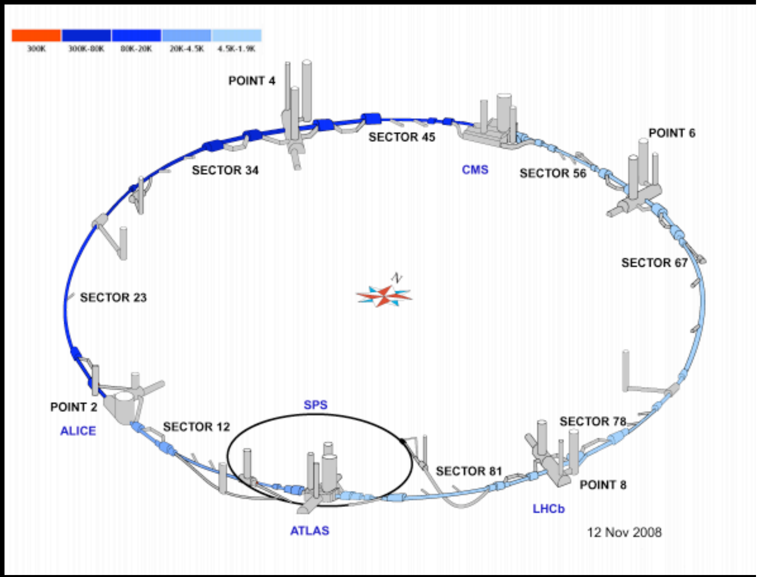
Pictures of the Damage





What's next?

- **Repair:**
  - 53 magnets need to be repaired
  - 28 magnets brought to the surface
  - First 2 replacements already back in the tunnel
- **Preventing it for the Future**
  - Additional valves will be installed to relieve pressure
  - Additional support structures to improve mechanical stability
  - New testing procedure was developed to spot the faulty connections
    - Found another one in sector 12 => being warmed up also



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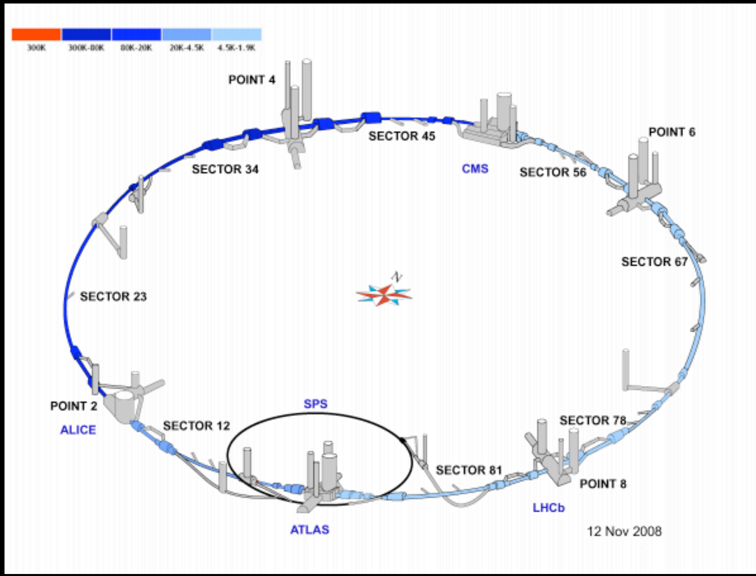


Schedule as of Dec. 5th:

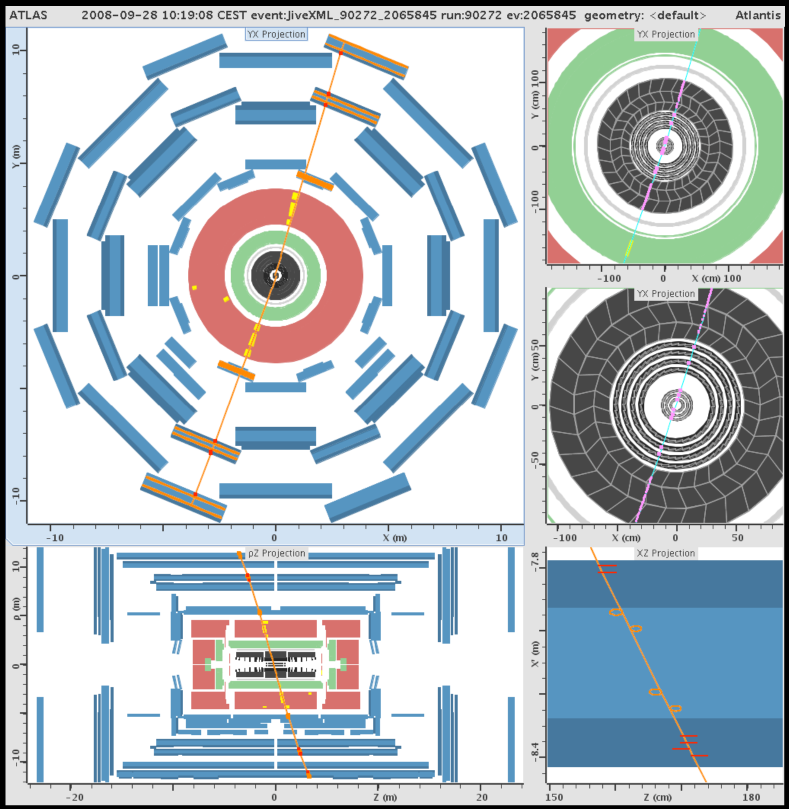
- machine cold end of June

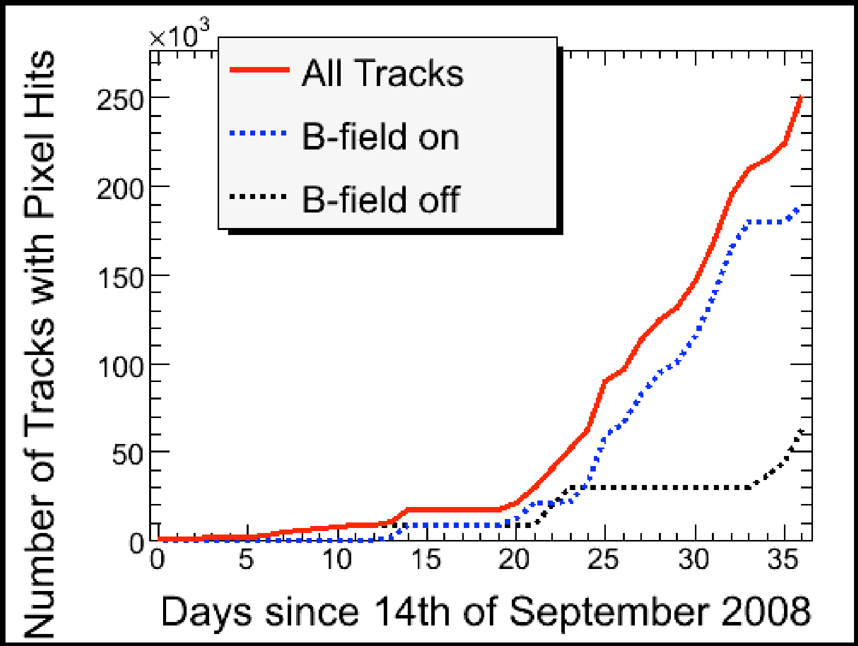
- beam 1 month later

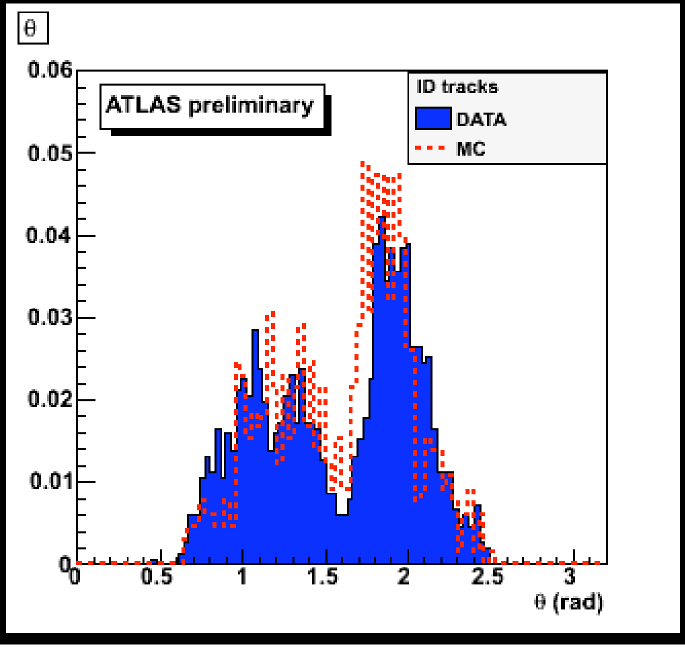
- energy to be decided

(for sure ≤5 TeV)

ATLAS Cosmic Running

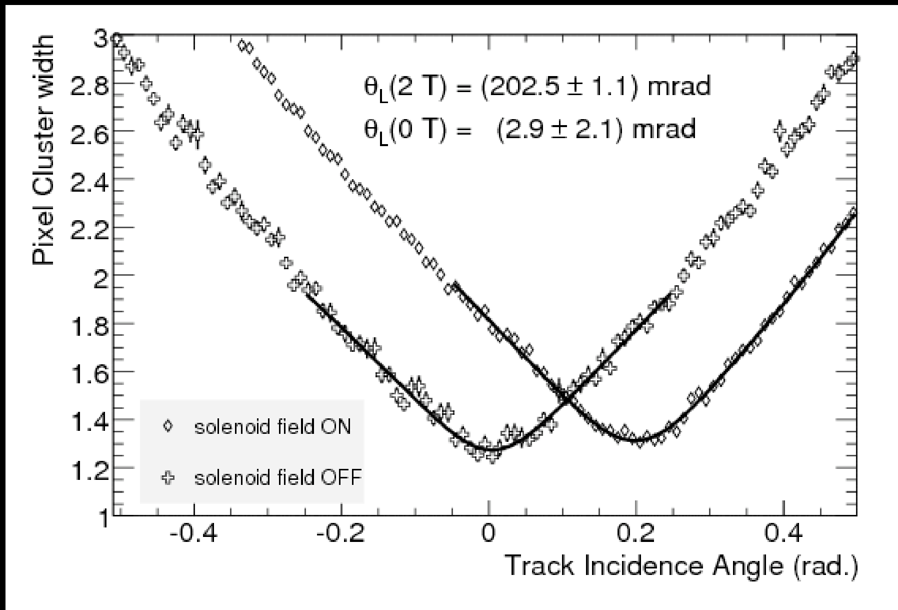


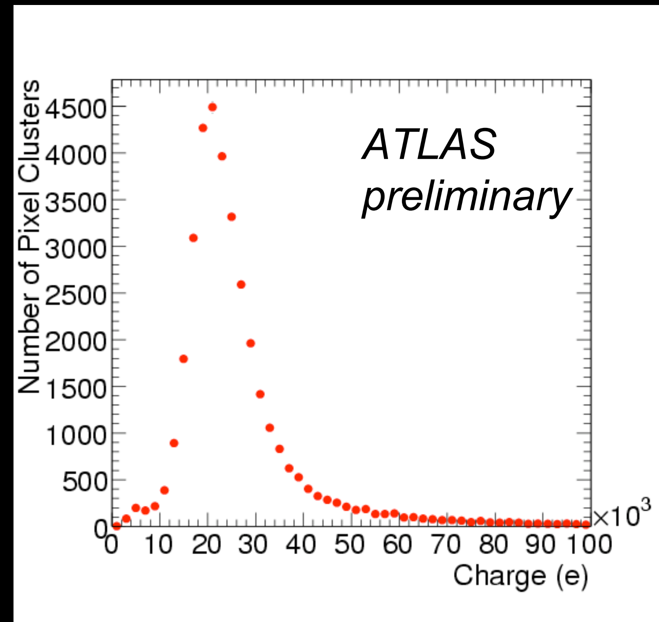




- Cosmic data taking with all subdetectors and 24/7 operation (>100 million of events)
  - Good operational exercise
  - Precious data for understanding detector response

Understanding the Pixel Detector with Cosmics





- Measurement of Lorentz Angle
- Charge calibration
- Position resolution
  - Improved from 331 μm to 31 μm
- Many more:
  - Hit efficiency, noise, timing…

Conclusions

- The LHC will finally probe the "TeV scale" ($r = 10^{-17}$ cm)
  - Known to be special since 1934
- The LHC will definitely answer some (and hopefully many) fundamental questions
  - What is the origin of mass?
  - Do supersymmetric particles explain the hierarchy problem and/or the Dark Matter?
  - … possibly more (extra spacial dimensions…)
- After a 15 year design and construction phase the LHC experiments first beam was seen
  - Major incidence with accelerator delayed collisions to next year
  - Meanwhile cosmic muons used to understand and optimize detector performance
- Hopefully next year first physics analyses can be done
  - Discoveries will likely come at least 2-3 years later